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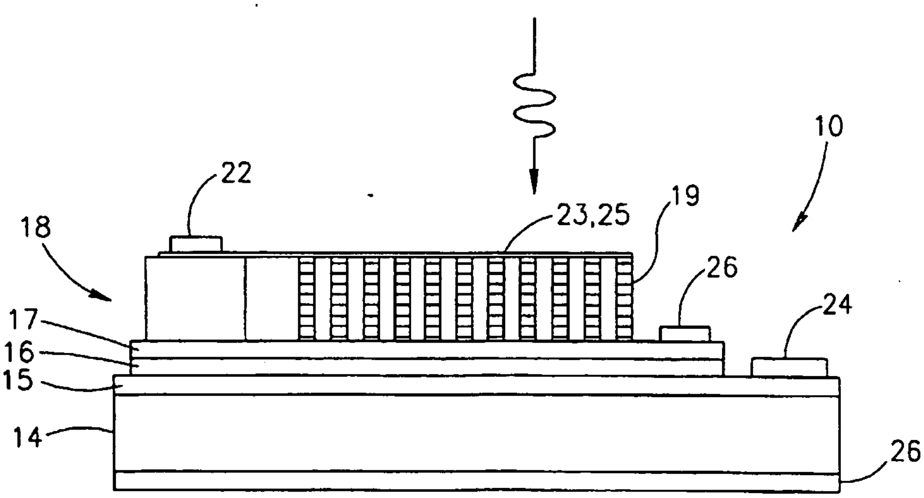
(54) Title: POLARIZATION SENSITIVE DETECTOR



(57) **Abstract:** Apparatus for detecting the polarization state of incident light, comprising: a first detector, which detects at least light having a first linear polarization, wherein part of the incident light is transmitted through said first detector to a second detector; and a second detector underlying the first detector which detects light passing through the first detector, at least a part of said detected light having a second polarization direction orthogonal to the first polarization; the ratio of light having said first and second polarizations detected by the first and second detectors being different for the first and second detectors when the incident light is normally incident on said first detector.

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For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

POLARIZATION SENSITIVE DETECTOR

FIELD OF THE INVENTION

The present invention is related to the field of detection of light and its polarization state by solid state or semiconductor detectors.

BACKGROUND OF THE INVENTION

The need for detecting not only the intensity of light but also the polarization state arises in many applications, such as optical data recording and readout or optical remote sensing. A common approach involves using a polarizing beam splitter to separate two orthogonal polarization components, and detect each polarization with a separate detector. This is both costly and space-consuming, and is not compliant with a trend towards planar systems which can easily be integrated with electronics.

US patent 5,767,507 to Unlu, el. al. describes a polarization sensitive photodetector utilizing resonant cavity enhanced (RCE) photodetectors. The RCE efficiency for different polarization states depends on the incidence angle of incoming light, enabling design of a detector sensitive to only one polarization state under some oblique incidence angle. Stacking two detectors with orthogonal sensitivities enables construction of a polarization photodetector that measures both the intensity and polarization of incident light.

Sub-Wavelength Structures (SWS) are gratings having a period which is smaller than the wavelength of light incident on them. For example, such structure can be a linear binary structure, etched into the surface of a semiconductor. Such a structure has different reflection and transmission properties for light having electric field polarization parallel to the grating (Transverse Electric, or TE) and perpendicular to it (Transverse Magnetic, or TM) . The SWS couples TE polarized light into evanescent diffraction orders that propagate inside it. As an example, the article "Subwavelength Transmission Gratings and Their Applications in VCSELs" by S.Y. Chou, S. Schablitsky and L. Zhuang, SPIE proceedings 3290, p. 73 ff., 1998 shows that a SWS etched in amorphous Silicon, at a period that equals 0.7 of the wavelength, gives zero transmission and 40% reflection for TE polarization, and 30% transmission, 10% reflectance for TM polarization, both for normal incidence of light. If the SWS is made from a material which absorbs the incident radiation (for example, Silicon for visible and near-IR light), the SWS will act as a polarization-sensitive absorber, or polarizer. This property of SWS is maintained over a relatively broad acceptance angle near perpendicular incidence, and is altered for more oblique incidence angles (e.g., close to Brewster's angle).

"Compact polarization sensors with vertically integrated photodetectors" by Bora M. Onat, et al., SPIE proceedings 3290, p. 52 ff., 1998 describes a system for determining polarization by stacking a polarization sensitive detector which preferentially detects and absorbs light having one polarization on top of a second sensor which is relatively insensitive to polarization. The detector can be calibrated such that the polarization of an incoming wave can be determined from the ratio of the light detected by the two detectors.

The described device utilizes a resonant cavity detector that is strongly incident angle and frequency dependent, for the outer detector and an ordinary detector for the inner detector. Since the outer detector preferentially absorbs light having the polarization for which it is dependent, the inner detector preferentially detects the other polarization, dependent on the angle of incidence and wavelength.

SUMMARY OF THE INVENTION

One aspect of some preferred embodiments of the present invention in its broadest form provides a polarization detector which is both compact and commensurate with planar semiconductor production techniques.

The polarization detection apparatus, in a preferred embodiment thereof, comprises a, preferably semiconductor, preferably monolithic, structure where a top element detects light having a component in at least one polarization direction and a bottom element detects light passing through the top detector. Preferably, the top and bottom elements have different ratios of sensitivity to light incident on the detector apparatus and having the one polarization and having a second polarization, normal to the first polarization.

In one preferred embodiment of the invention, the top detector is intrinsically more sensitive to the one polarization. In other preferred embodiments of the invention, the top detector is substantially insensitive to polarization. Preferably, a polarizer is provided between the two detectors.

An aspect of the invention is concerned with methods and apparatus for measuring the power of both polarization states of the incoming light, with broad acceptance angle and in particular for perpendicular illuminating light.

1. There is thus provided, in accordance with a preferred embodiment of the invention, apparatus for detecting the polarization state of incident light, comprising:

a first detector, which detects at least light having a first linear polarization, wherein part of the incident light is transmitted through said first detector to a second detector; and

a second detector underlying the first detector which detects light passing through the first detector, at least a part of said detected light having a second polarization direction orthogonal to the first polarization;

the ratio of light having said first and second polarizations detected by the first and second detectors being different for the first and second detectors when the incident light is normally incident on said first detector.

Preferably, light having said first polarization is preferentially absorbed by the first detector as compared with light having the second polarization.

Preferably, the first detector is in the form of a sub-wavelength grating structure, SWS.

There is further provided, in accordance with a preferred embodiment of the invention, apparatus for detecting the polarization state of incident light, comprising:

a first detector, which detects incident light with a sensitivity that is not a function of the polarization of the incident light, wherein part of the incident light is transmitted through said first detector to a second detector; and

a second detector underlying the first detector which detects light passing through the first detector, said second detector detecting light incident on the apparatus at a second polarization with greater sensitivity than it detects light incident to it at a first polarization, orthogonal to the second polarization.

Preferably, the first detector is a substantially non-resonant detector.

Preferably, light having said first polarization is absorbed by the first detector in substantially the same proportion as light having the second polarization.

In a preferred embodiment of the invention, the apparatus includes a polarizer between the first and second detectors. Preferably, the polarizer is a sub-wavelength grating structure, SWS.

In preferred embodiments of the invention, the apparatus is comprised in a monolithic device.

Preferably, the detectors are semiconductor detectors.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention will be more clearly understood from the following description of preferred embodiments of the invention read in conjunction with the attached drawings in which:

Figs. 1A and 1B schematically illustrate a polarization detector, in accordance with a preferred embodiment of the invention; and

Fig. 2 is a schematic representation of a second polarization detector, in accordance with a preferred embodiment of the invention.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

Figs. 1A and 1B schematically illustrate a polarization detector structure 10, according to a preferred embodiment of the invention, for detection of radiation 11 incident thereon. Structure 10 comprises a bottom detector 14, preferably separated by an insulating, preferably transparent, dielectric layer 16 from a top detector 18. Fig. 1A shows a cross section through a polarization detector, while Fig. 1B depicts a top view of the same structure.

A back side of detector 14 is electrically connected to a first electrical contact 20. A front side of detector 14 is electrically connected to a second electrical contact 24. Electrical contacts 22 and 26 are used to contact the front and back sides respectively, of detector 18. A layer 17, preferably a transparent conductor, such as Indium Oxide, or a doped semiconductor layer provides a connection between contact 26 and the back of detector 18. Dielectric layer 16 is preferably used as an insulator that electrically separates the two detectors. Preferably, a second conductive transparent layer 15 is provided between detector 14 and dielectric layer 16. This provides a good, low impedance connection between contact 24 and the front surface of detector 14.

Alternatively, the voltage at conductors 24 and 26 are the same and dielectric layer 16 is omitted and only a single conductive and at least partially transparent layer is utilized. In this case, the conductive layer between the detectors is conveniently formed of a highly doped layer of the same material used for detectors 14 and 18.

While not shown explicitly on Figs. 1A and 1B, a light blocking layer, such as a layer of metal, is preferably provided overlaying those areas of the lower detector that are not covered by the SWS device. This assures that all of the light detected by the lower detector has passes through the upper detector and been modified by it. Furthermore, it provides for equal areas of detection for the two detectors. Such masking of the lower detector is preferred for other embodiments of the invention as well. Alternatively, as indicated below, a mask is provided to limit the extent of the light incident on the top detector.

According to a preferred embodiment of the invention, detectors 14 and 18 are doped silicon positive-intrinsic-negative (PIN) photo detectors. Alternatively, detectors 14 and 18 can comprise positive-negative (PN) silicon photo detectors or other doped semiconductor detector structures (e.g., GaAs, GaInAs, GaInAsP). The detectors 14 and 18 may also be integrated with electronic devices for amplification and processing the two detector outputs. The detectors may

be constructed utilizing any suitable known methods of semiconductor fabrication including combinations of ion implantation, epitaxial growth, diffusion, oxidation, sputtering, plating or other methods as known in the art.

A preferred embodiment for two detectors capable of detecting orthogonal polarization states of a light beam is established by stacking the detectors one on top of the other, making the top detector 18 sensitive and absorbing for one polarization direction while transmitting the other, and the bottom detector 14 differentially more sensitive to light 10 having the orthogonal polarization. The bottom detector 14 can also be sensitive to both polarization states provided that detector 18 transmits substantially only one polarization, and absorbs or reflects the orthogonal polarization and the bottom detector is masked so that only light passing through the top detector is detected by it.

A method, according to a preferred embodiment of the invention for making a substance such as silicon, absorb only one type of polarization is by forming detector 18 as a sub-wavelength structure (SWS) formed of elements 19. As indicated, the upper face of elements 19 are covered by a transparent conductor 23. This conductor may be a metal conductor or, more preferably, a highly doped layer of structures 25 and 19. The individual conductors on elements 19 are connected to conducting pad 22 by conductor 23 on an element 25 formed in the same manner as elements 19. Preferably, only an area covered by elements 19 (such as, for example, the dotted area indicated by reference number 27 in Fig. 1B) receives incident light. The area outside area 27 is preferably masked by a mask (not shown) to shield it from incident light. It should be understood that if the light impinging on the detector is focused, masking may not be necessary.

Thus, detector 18 is patterned by a preferably linear (one-dimensional), conveniently binary design (elements 19) SWS with period preferably less than the wavelength of the light, ideally designed to absorb only a single polarization direction and transmit only the other polarization state to bottom detector 14. The optical depth of the top layer pattern is preferably a quarter of the design wavelength (or a whole multiple of half the wavelength plus a quarter wavelength), to obtain minimum reflection from the structure. When the grating period is slightly smaller than the wavelength (preferably 0.6-1.0 wavelengths) the pattern acts as a polarizer, absorbing one polarization and transmitting the other (the distance between pattern lines in SWS 19 in Fig. 1 are exaggerated for clarity). The polarization properties of the SWS are determined for perpendicular incidence of light, and are maintained over a relatively broad

acceptance angle. Large oblique incidence angles (for example, at Brewster's angle) will alter the polarization properties.

Making the SWS a PN or PIN junction by proper doping of the material and using electrodes 22 and 26 to connect to it, constitute a polarized detector 18, a detector which is sensitive only to a single polarization and transmits the other polarization. Preferred embodiments of the present invention involve creating a polarization detector pair 10 by stacking such a polarization sensitive detector 18 on top of an additional, preferably regular photodiode 14, or on another, preferably, orthogonal polarized detector 14 (for example if the rejection ratio of the first polarizer is too low). Ideally, the top detector 18 absorbs only TE polarized light, transmitting at least a major portion of the TM polarized light (and ideally no TE light) to the bottom detector 14 which thus detects only the TM polarization.

The depth of the SWS top detector 18 is determined by allowing enough absorption of the TE polarization (based on the absorption coefficient of the material and internal reflections of the incident light at the interfaces) while minimizing reflectance of both polarization states from the structure.

Fig. 2 shows a side view of another type of a polarization detector structure 30, according to a preferred embodiment of the invention. The parts of the figure that are identical with or analogous with parts of Fig. 1 are given the same number references for clarity.

Polarization detector 30 comprises a bottom detector 14, an insulating, preferably transparent polarizing layer 31, and a top detector 32. While Fig. 1 shows a top polarized detector 18, the top detector 32 in the configuration of Fig. 2 is not polarized, but is a standard photodiode detector adjusted for small light absorption, preferably about 50%. The signal measured by detector 32 corresponds to the sum of contributions from both orthogonal polarization directions of the incident light. The part of the light that passes through detector 32 is polarized by polarizing layer 31, which is composed either of SWS of two materials having different refractive indices (e.g., Silicon and Silicon Oxide), or of some other polarizing material (e.g., polymer polarization sheet). This structure lends it self to construction using semiconductor polymer fabrication techniques. The transmitted light to detector 14 is polarized in the same direction as polarizing layer 31. Detector 14 is, as in Fig. 1, conveniently a photodiode.

As in Fig. 1, if electrodes 24 and 26 are at the same voltage, no dielectric layer is required (and none is shown in Fig. 2). However, two conductors are conveniently provided,

since structure 31 does not conduct over its entire area and conducts only in one transverse direction.

While polarized detector 14 measures one polarization component of the incoming light, the orthogonal component power is obtained by subtracting the output of detector 14 from the output of detector 32, taking into account scaling factors for different sensitivities of the detectors and losses in the light path. Thus for example, for 50% absorption and 50% transmission by detector 32, the difference between detector 32 measurement and detector 14 measurement provides a measurement of the polarization orthogonal to polarizing layer 31 direction. Deviation from 50% requires scaling the two measurements for exact measurement of the orthogonal polarization.

First detector 32 may be a detector which is not polarization dependent (such as an ordinary non-resonant detector) or it may have a polarization dependent sensitivity.

It should be noted that the described invention is applicable to structures utilizing most semiconductor materials as well as to composite semiconductor and non-semiconductor systems. Furthermore a variety of detector structures may be used and the structure can be designed to operate in various wavelength regions.

The present invention has been described in conjunction with a number of preferred embodiments thereof which combine various features and various aspects of the invention. It should be understood that these features and aspects may be combined in different ways and various embodiments of the invention may include one or more aspects of the invention. For example the first detector may be polarizing as in Fig. 1 and a polarizer may be provided, between the first and second detectors as in Fig. 2, to improve the separation of the detection of the two polarizations between the detectors. The scope of the invention is defined by the claims and not by the specific preferred embodiments described above. As used in the present application, the terms "comprise", "have" and "include" and their conjugates means "including but not limited to".

CLAIMS

1. Apparatus for detecting the polarization state of incident light, comprising:

a first detector, which detects at least light having a first linear polarization, wherein part of the incident light is transmitted through said first detector to a second detector; and

a second detector underlying the first detector which detects light passing through the first detector, at least a part of said detected light having a second polarization direction orthogonal to the first polarization;

the ratio of light having said first and second polarizations detected by the first and second detectors being different for the first and second detectors when the incident light is normally incident on said first detector.

2. Apparatus according to claim 1 wherein light having said first polarization is preferentially absorbed by the first detector as compared with light having the second polarization.

3. Apparatus according to any of the preceding claims wherein the first detector is in the form of a sub-wavelength grating structure, SWS.

4. Apparatus for detecting the polarization state of incident light, comprising:

a first detector, which detects incident light with a sensitivity that is not a function of the polarization of the incident light, wherein part of the incident light is transmitted through said first detector to a second detector; and

a second detector underlying the first detector which detects light passing through the first detector, said second detector detecting light incident on the apparatus at a second polarization with greater sensitivity than it detects light incident to it at a first polarization, orthogonal to the second polarization.

5. Apparatus according to any of the preceding claims, wherein the first detector is a substantially non-resonant detector.

6. Apparatus according to any of claim 1, 4 or 5 wherein light having said first polarization is absorbed by the first detector in substantially the same proportion as light having the second polarization.

7. Apparatus according to any of the preceding claims, and including a polarizer between the first and second detectors.

8. Apparatus according to claim 7 wherein the polarizer is a sub-wavelength grating structure, SWS.

9. Apparatus according to any of the preceding claims wherein the apparatus is comprised in a monolithic device.

10. Apparatus according to any of the preceding claims wherein the detectors are semiconductor detectors.

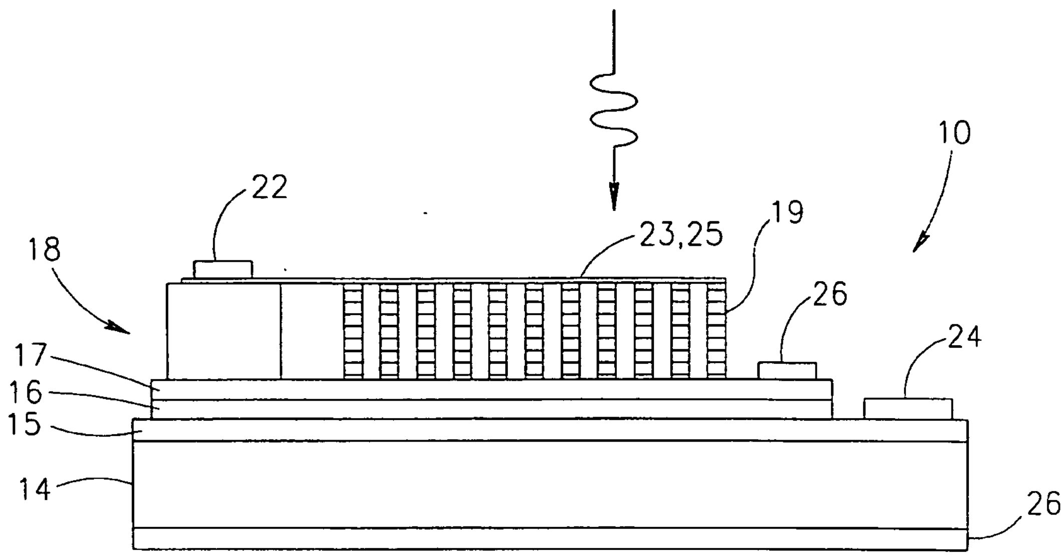

FIG.1A

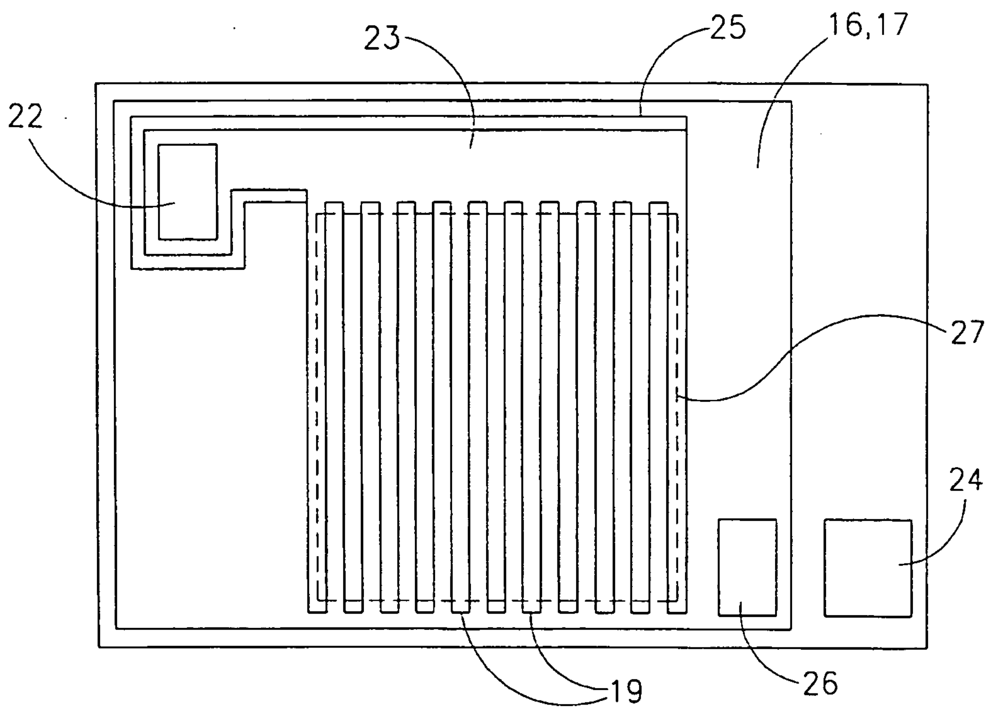

FIG.1B

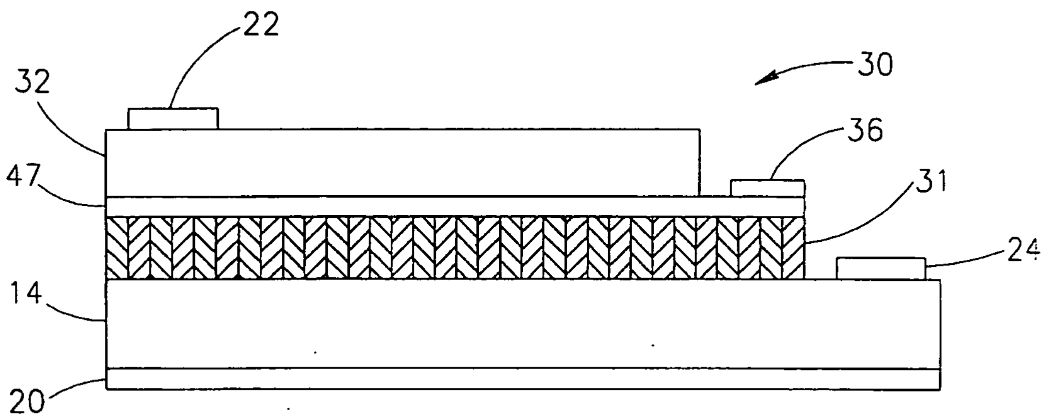

FIG.2

INTERNATIONAL SEARCH REPORT

International Application No
PCT/IL 99/00705

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 H01L31/0236 H01L31/11 //G01J5/04

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 H01L

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 5 767 507 A (ONAT BORA ET AL) 16 June 1998 (1998-06-16) cited in the application figure 5 column 8, line 12 -column 9, line 45	1-10
Y	US 5 539 206 A (SCHIMERT THOMAS R) 23 July 1996 (1996-07-23) figure 6 column 7, line 31 - line 48 column 8, line 28 - line 30	1-3,9,10

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[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

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"P" document published prior to the international filing date but later than the priority date claimed

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"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
20 April 2000	04/05/2000

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Visscher, E

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International Application No
PCT/IL 99/00705

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT		
Category °	Citation of document, with indication where appropriate, of the relevant passages	Relevant to claim No.
Y	CHEN E ET AL: "A NOVEL DEVICE FOR DETECTING THE POLARIZATION DIRECTION OF LINEAR POLARIZED LIGHT USING INTEGRATED SUBWAVELENGTH GRATINGS AND PHOTODETECTORS" IEEE PHOTONICS TECHNOLOGY LETTERS,US,IEEE INC. NEW YORK, vol. 9, no. 9, 1 September 1997 (1997-09-01), pages 1259-1261, XP000721228 ISSN: 1041-1135 abstract section II:device design and performance ---	4-8
A	DOUMUKI T ET AL: "AN ALUMINUM-WIRE GRID POLARIZER FABRICATED ON A GALLIUM-ARSENIDE PHOTODIODE" APPLIED PHYSICS LETTERS,US,AMERICAN INSTITUTE OF PHYSICS. NEW YORK, vol. 71, no. 5, 4 August 1997 (1997-08-04), pages 686-688, XP000699633 ISSN: 0003-6951 the whole document -----	1-10

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No
PCT/IL 99/00705

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